Annals of Glaciology 37 2003

Spatial stability of Ice Stream D and its tributaries, West Antarctica, revealed by radio-echo sounding and interferometry

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ABSTRACT. It has been shown recently that ice streams are fed by fast-flowing tributaries occupying well-defined subglacial troughs and with shared source areas. Here, ice-penetrating radio-echo sounding (RES) data are analyzed in conjunction with ice surface velocities derived from interferometric synthetic aperture radar (InSAR), to determine the englacial properties of tributaries feeding Ice Stream D, West Antarctica. All of Ice Stream D's tributaries are coincident with "buckled" internal ice-sheet layers, most probably deformed by the processes responsible for enhanced ice flow. Between the tributaries well-preserved internal layers occur. The data reveal that no lateral migration of the ice-stream tributaries has occurred recently. This is consistent with thermomechanical ice-flow modelling, which indicates that the flow of Ice Stream D is controlled by a subglacial trough and is unaffected by changes to the flow of neighbouring Ice Stream C.

INTRODUCTION

Understanding how ice streams function is critical to evaluating the stability of the West Antarctic ice sheet. Interferometric synthetic aperture radar (InSAR), detailing the surface velocity of ice, and balance-flux modelling have shown that ice feeds into ice streams through a complex system of tributaries that extend several hundred kilometres into the ice-sheet interior (Joughin and others, 1999; Bamber and others, 2000). Although knowledge of these tributaries is crucial to our understanding of ice streams, there is currently no consensus on the evolution and spatial behaviour of these systems.

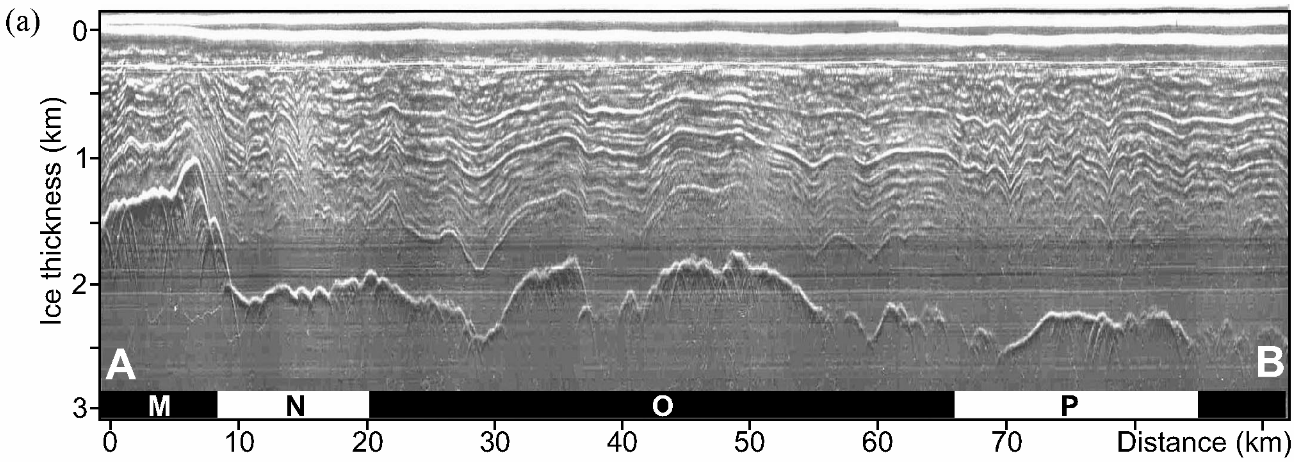
It has been argued that the spatial configuration of ice streams and their tributaries may change with time. For example, Ice Stream C is thought to have experienced at least three major changes to its configuration. First, buried surface crevasses show that about 150 years ago the ice stream "switched" from flowing rapidly to its current inactive state (Retzlaff and Bentley, 1993). Second, warped internal layers and surface scar features indicate that, prior to 1300 years ago, part of Ice Stream C flowed north of the Siple Dome into Ice Stream D, whereas after this time the mouth was positioned entirely south of the dome (Jacobel and others, 1996). Third, a combination of surface and satellite derived measurements shows that ice that once flowed into Ice Stream C is now routed through Whillans Ice Stream (known formerly as Ice Stream B) (Conway and others, 2002). Given that the dynamics of Ice Stream C alter with time, it is important to assess how neighbouring ice streams change as a consequence of both their own internal dynamics and the configuration of Ice Stream C.

ENGLACIAL PROPERTIES OF ICE STREAM D

Ice-penetrating radio-echo sounding (RES) data have been used to map the large-scale characteristics of Siple Coast ice streams (Rose, 1978, 1979), such as subglacial morphology (Fig. 1), and, in some places, fine details (Jacobel and others, 1996). Internal ice-sheet layers, recorded in RES data, are

Fig. 1. Map of the bedrock morphology around the Siple Coast, West Antarctica. Whillans Ice Stream and Ice Streams C, D and E are located. The position of the Bentley Subglacial Trench is also noted. RES flight-lines, discussed later, are superimposed on the map and are coded as in Figure 4.

https://doi.org/10.3189/172756403781816022 Published online by Cambridge University Press



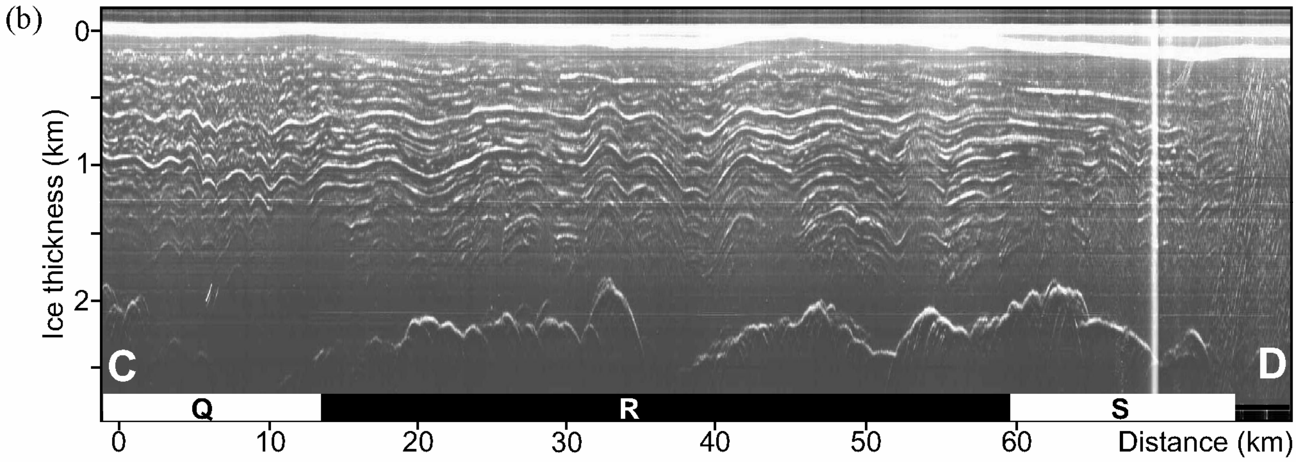


Fig. 2. Examples of 60 MHz airborne RES data across tributaries of Ice Stream D. (a) AB, where two regions of buckled internal layers (N and P) are separated by a 45 km long section of well-preserved layers (O). (b) CD, in which two areas of buckled layers (Q and S) lie either side of the well-preserved layers (R). The locations of the transects and their relationship to ice-flow units are provided in Figure 4. Spectral analyses of layers and bed profiles for regions O, P, Q and R are shown in Figure 3. Internal layers in the Antarctic ice sheet, recorded by ice-penetrating RES, are understood to be formed by ice-density variations in the upper 700–900 m of the ice sheet, and acidic layers of ice caused by the aerosol product of volcanic events deposited formerly on the ice surface (Fujita and others, 1999). Under conditions of enhanced shear stress, layers of contrasting ice crystal-orientation fabric may develop from acidic-based layers.

generally continuous and traceable over hundreds of kilometres in ice that has experienced relatively slow flow (Robin and Millar, 1982). In ice streams, however, this layering is often deformed or even destroyed (Jacobel and others, 1993). Across the transition from slow ice flow to rapid tributary flow, the well-preserved internal layers are observed to buckle or warp (Bell and others, 1998). Downstream along a tributary, ice is subject to further deformation (Jacobel and others, 1993) until the layering is eventually obliterated.

In austral summer 1974/75, an airborne ice-penetrating RES campaign involving the Scott Polar Research Institute, U.K., the U.S. National Science Foundation and the Technical University of Denmark acquired ~20 000 km of flight track over Marie Byrd Land, West Antarctica. The RES transects were arranged as a square grid, with 50 km separating each line. The survey covered approximately 600 000 km^2 of the ice sheet. The data were obtained using a frequency of 60 MHz and a pulse width of 240 ns. Ice thicknesses were calculated from the two-way travel time of 60 MHz radio waves in ice, and a wave-propagation speed of 168 m μs^{-1} in ice (NB: the two-way travel through air must also be accounted for).

These RES data were analyzed to determine the pattern of internal layering across areas upstream of Ice Stream D. The distribution of three types of ice was mapped according to whether internal layers are (1) preserved well, (2) buckled or warped, or (3) absent or deformed beyond recognition as continuous reflectors (Fig. 2). Although the latter category can be identified confidently, the absence of layers is often caused by the loss of the radio-wave power sent into the ice sheet as a consequence of an increase in the aircraft altitude above the ice surface. Our analysis is therefore limited to the former two types of internal layering. Qualitatively, however, there is often a problem in deciding whether layers are buckled or not, and, to complicate the matter further, some internal layers appear more buckled than others. The criteria used to classify internal layers therefore need to be clear. For internal layers that are "well preserved", the amplitudes of all undulations (wavelengths) are less than those of the bed, and the dominant wavelengths of the bed and layers are similar. This criterion was developed following the work of Robin and Millar (1982) who noted that the relief of well-preserved internal layers is never rougher than the bed relief. Conversely, if the layers are classified as "buckled", the amplitudes of the relatively short wavelengths, at around 500–5000 m, are greater than those of the bed. Spectral analyses were performed to quantitatively verify the qualitative classification of RES layering. For

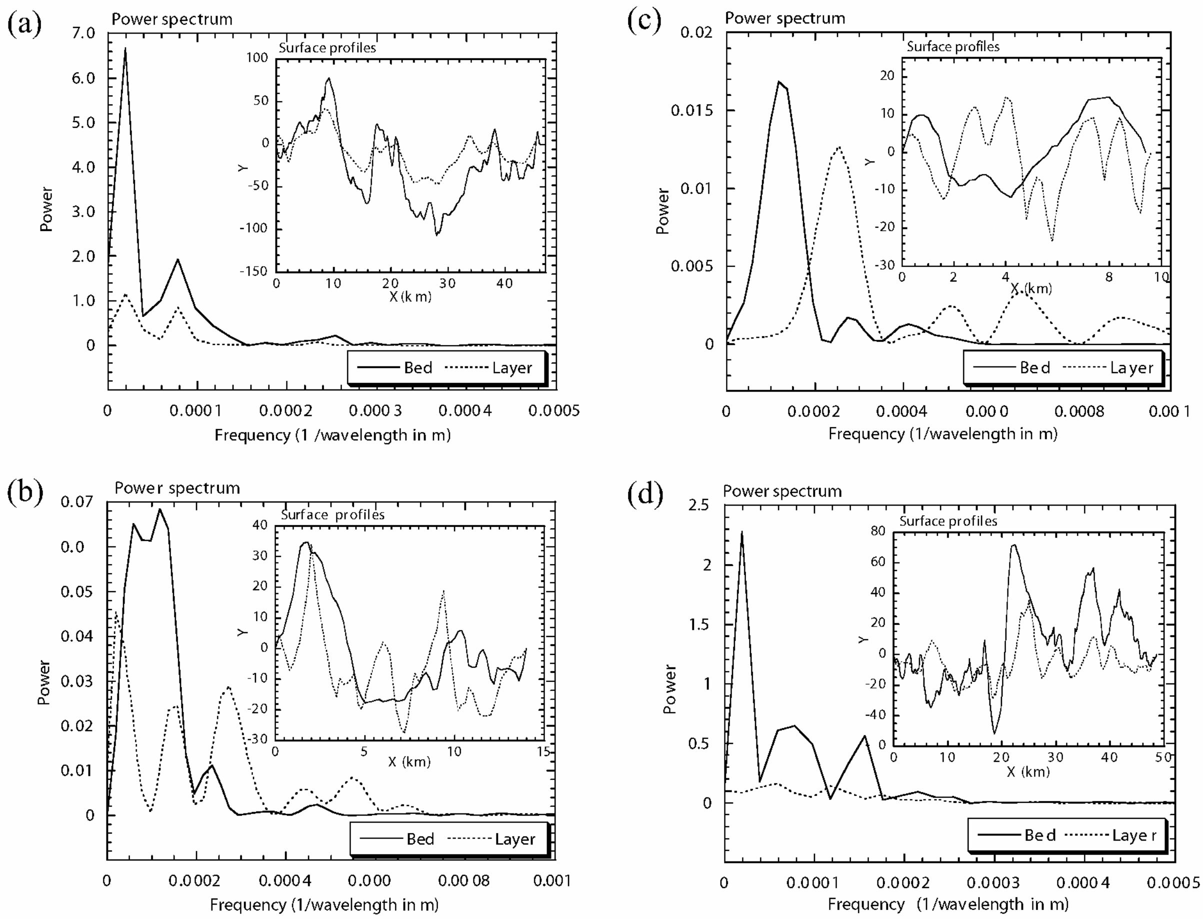


Fig. 3. Spectral analysis of subglacial bed and internal layer profiles at locations marked in Figure 2: (a) site O; (b) site P; (c) site Q; and (d) site R. Examples where the internal layers are classified as "well preserved" are provided in (a) and (d), whereas (b) and (c) illustrate "buckled" internal layers. The raw surface profiles from which each spectral analysis was performed are provided in the inset to each power spectrum graph. For well-preserved internal layers, the dominant frequencies are similar to, and less powerful than, those of the bed. Conversely, buckled layers show greater powers at shorter wavelengths (or greater frequencies) than the bed. Note that no units are needed for the y axis of the surface profiles, since the relative power spectra for layer and bed will be dependent only on the relative vertical displacement.

each individual classification, a continuous internal layer, selected from the centre of the ice column, was digitized with a sample space of 200 m. The data were then standardized so that the offsets at the beginning and end of a profile were zero. Fast Fourier transforms were then performed on the surface profiles and, from this calculation, power spectra were produced. Four examples of the spectral analysis of bed and internal layer profiles are provided in Figure 3. If the layers are not continuous but still visible, spectral analysis on individual layers is not possible, and they are classified qualitatively as "buckled". It should be noted that no attempt is made to quantify the degree of layer buckling or determine the mechanics responsible for "buckled" internal layering. It is likely that buckled layers occur as a consequence of high longitudinal stresses within regions of enhanced ice flow, and lateral shear stresses at the transition of fast- and slow-flowing parts of the ice sheet (Jacobel and others, 1993). The assumption made in this paper is that these stresses occur as a consequence of enhanced ice flow, and that internal layers will become more buckled the longer such stresses are applied.

Along each RES line, the classification of internal layering was coded (black thin lines for no layering; white thick lines for buckled layering; black thick lines for well-preserved layering). The annotated RES transects were then superimposed over InSAR data showing ice surface velocities (Fig. 4).

For Ice Stream D, most buckled internal layers are coincident with tributaries, and between all the tributaries the ice possesses well-preserved layering (Fig. 4). This coincidence suggests that Ice Stream D's tributaries are well defined spatially and have not experienced significant lateral migration recently. There is some evidence, however, of minor lateral migration. For example, at site B (Fig. 4) the layering suggests that the tributary should be narrower than it actually is, indicating recent widening of the tributary. Further south from site B, the zone of buckled internal layers is wider than the current tributary, indicating that it has narrowed here. There are no signs, however, of major changes to the flow paths, as the inter-tributary regions are dominated by well-preserved internal layering.

Between the onset regions of Ice Streams C and D there is a large area of well-preserved internal layers, marking the slow-flowing boundary between these fast-flow units. The well-defined buckling of internal layers within Ice Stream D's tributaries is in contrast to the situation in the Bentley Subglacial Trench. Here internal layers are extremely well preserved. Ice flow through the deformation of ice is thought to dominate glacial dynamics in this trough, despite the base being at the pressure-melting temperature (Hulbe and

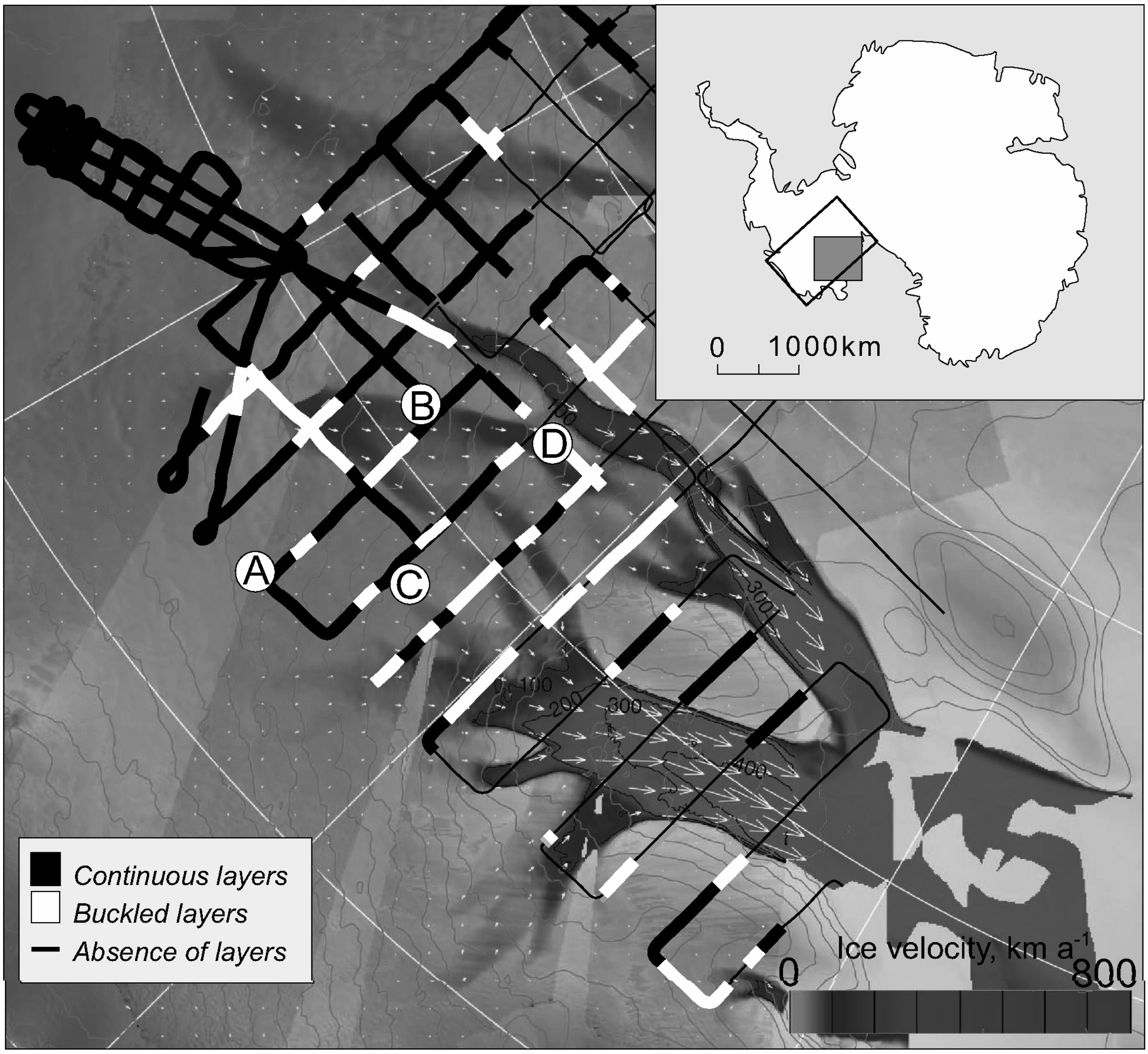


Fig. 4. Interpreted RES data superimposed over InSAR data. The RES data are coded as follows: thin line = no layering; white = buckled layering; black = well-preserved layering. The position of two RES transects AB and CD, detailed in Figure 2, is illustrated. The ice-flow velocity was derived using a combination of conventional interferometry and speckle-tracking methods applied to RADARSAT data collected during the first Antarctic Mapping Mission (AMM-1). Velocities in the downstream areas of Ice Streams D, E and F also include data (Bindschadler and others, 1996) generated by tracking features visible in pairs of Landsat or other images. A small gap in the upper catchment of Ice Stream D was filled using global positioning system (GPS)-derived velocities from a dense (5 km) survey grid (Chen and others, 1998). Errors in each component of velocity are generally $< 5\,\mathrm{m\,a^{-1}}$ and spatial resolution varies from roughly 0.5 to 3 km. The locations of the InSAR map (shaded box) and the domain of the numerical modelling presented in Figure 5 (open box) are provided in the inset.

MacAyeal, 1999). The well-defined internal layers demonstrate that the processes active within the tributaries of Ice Stream D, causing the layers there to buckle, have not acted over the Bentley Subglacial Trench at least since the Last Glacial Maximum (the approximate age of the deepest layers according to the depth–age relationship of the nearby Byrd ice core (Johnsen and others, 1972; Whillans, 1976)).

ICE-SHEET MODEL RESULTS

Thermomechanical modelling of the West Antarctic ice sheet supports the notion that Ice Stream D is a relatively stable feature (Payne, 1998, 1999). Furthermore, the modelling shows that this stable behaviour is in contrast to that of neighbouring Ice Stream C.

The model calculates ice flow into Ice Streams C, D and Whillans Ice Stream, and can be used to investigate how ice-flow paths change as a consequence of internal ice-sheet dynamics. It predicts that the upstream drainage configuration of Ice Stream D is relatively stable, even though Ice Stream C is susceptible to major flow-path changes over a period of about 10 kyr. These changes are characterized in two end-member states. In one state, ice flows into Ice Stream C from a wide upstream catchment that is centred on the Bentley Subglacial Trough (Figs 1 and 5b). In the second state, Ice Stream C is essentially stagnant and ice flow from the Bentley Subglacial Trough area is via an enhanced Whillans Ice Stream (Fig. 5a). This modelled variability is a consequence of the interaction between ice flow and thermal regime, whereby fast-flowing ice generates more heat that softens the ice and promotes even faster flow (here the model

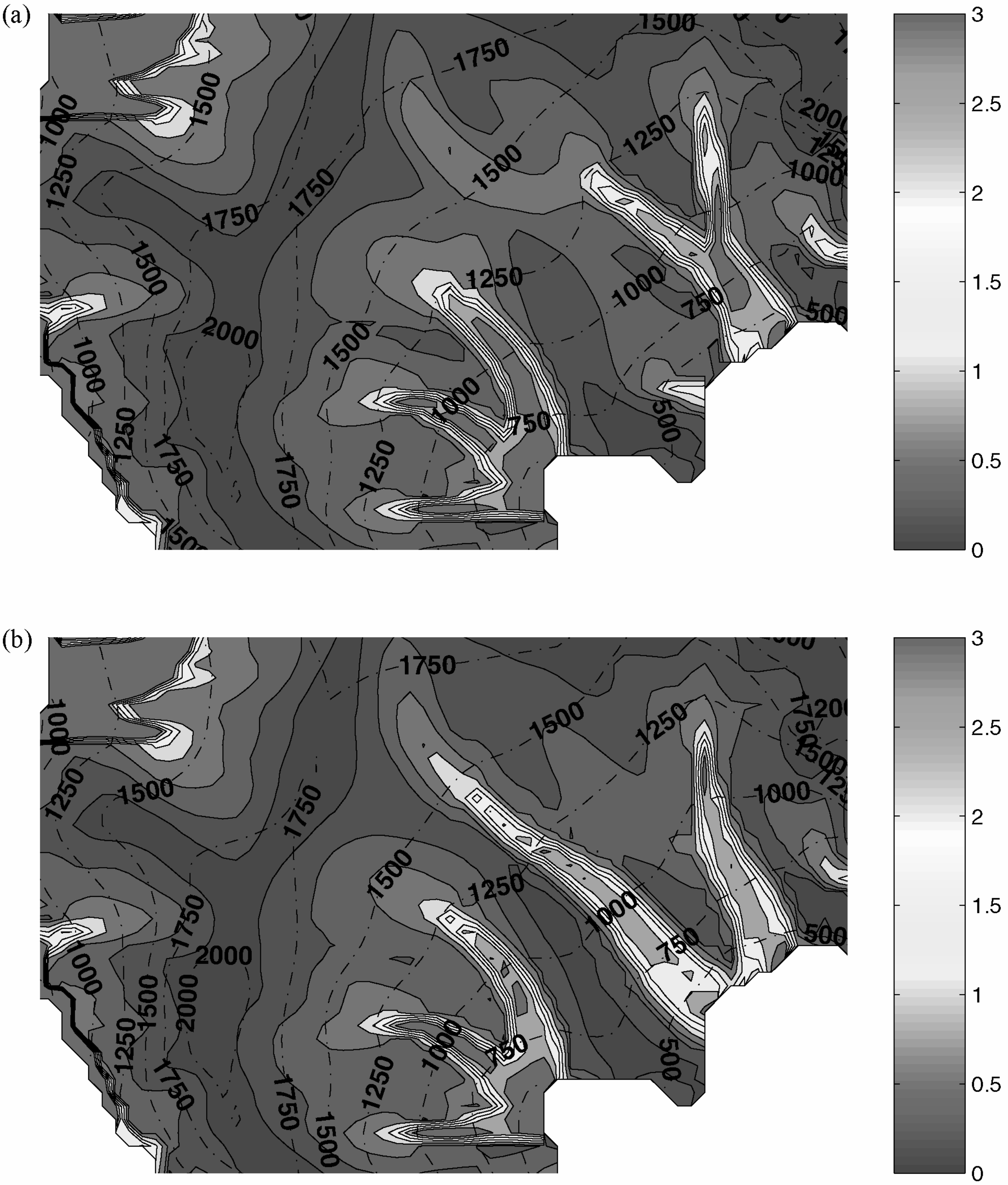


Fig. 5. Results from numerical modelling of the West Antarctic ice sheet (Payne, 1998, 1999). The figure shows modelled ice flux ($10^5\ m^2\ a^{-1}$) overlain by contours of surface elevation (m) for a time (a) when modelled Ice Stream C is inactive and (b) when it is active (separated in the model by approximately 10 000 years). The model domain shown is roughly 1200 by 800 km in size, with the Ross Ice Shelf (not modelled) located at the bottom right of the diagram and the Ruppert Coast at the bottom left (see inset of Fig. 4).

assumes a local balance between gravitation driving stress and vertical shear stresses on spatial scales of 20 km). This interaction is prompted by bedrock topography. In the case of Whillans Ice Stream and Ice Stream C, there are several closely spaced subglacial troughs that encourage this enhanced ice flow. The result is a number of ice streams that compete with one another and generate a repeating cycle of growth and stagnation. In the case of Ice Stream D, however, there is only one trough that the ice stream can occupy (Fig. 1). The ice-flow paths upstream of Ice Stream D are therefore maintained regardless of substantial changes to the ice-flow direction nearby in Ice Stream C.

The mechanism by which ice streams actually stagnate in the model (by freezing to the underlying substrate) is not compatible with the data of Bentley and others (1998) who show that the bed of Ice Stream C is not frozen although the stream is stagnant. However, a plastic model has recently been proposed for the rheology of the till underlying the ice streams (Tulaczyk and others, 2000). Such a model allows the bed to stiffen dramatically upon the loss of small amounts of water via freezing on, which implies that the onset of freezing may still be an important stage in ice-stream stagnation.

The concept of competing ice streams affecting one another's flow offers an explanation for why Ice Stream D can maintain stability while Whillans Ice Stream and Ice Stream C show variability. The competition itself arises from the contrasting subglacial topography of Ice Stream D compared with Whillans Ice Stream and Ice Stream C.

CONCLUSIONS

The stability of ice streams is critical to evaluating the long-term fate of the West Antarctic ice sheet. Ice Stream C is thought to have experienced at least two major changes to its configuration. One occurred >1000 years ago and resulted in a change in the ice-stream flow direction; a second took place only 150 years ago, and caused the ice stream to "switch off". RES and InSAR data indicate, however, that ice-flow paths feeding into Ice Stream D have been stable recently. Fast-flowing ice-stream tributaries, identified by InSAR, are coexistent with warped internal layering, whereas the inter-tributary zones have well-preserved internal layers. Thermomechanical ice-sheet modelling supports the notion that Ice Stream D has been stable in the past. The model suggests that subglacial topography is a major determinant of spatial stability. In the case of Ice Stream C and Whillans Ice Stream, there are a number of subglacial troughs in which the ice streams may flow, whereas for Ice Stream D there is only one major channel that dominates the ice-stream dynamics.

ACKNOWLEDGEMENTS

Funding for this work was provided by the U.K. Natural Environment Research Council (NERC) Centre for Polar Observation and Modelling. We thank B. P. Hubbard (University of Wales Aberystwyth) for providing technical assistance during the spectral analysis of internal layers, and the Director of the Scott Polar Research Institute, University of Cambridge, for access to RES data.

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